International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Heat Transfer Improvement in A Parabolic Trough Receiver

[1]Ashok Singh Yadav, [2]Varun Brijpuria

[1]M-Tech (Student), [2]HOD (Mechanical Engg. Dept.)
Shri Ram Institute of Science and Technology Jabalpur

ABSTRACT :

The objective of this study is to numerically investigate the incorporation of wall-attached internal fins in a parabolic trough receiver in order to enhance its heat transfer efficiency. A variety of fin geometries that are right triangle, obtuse triangle and isosceles triangle were evaluated and compared with the smooth parabolic trough receiver. In addition to the different fin shapes, simulations were conducted for tubes with one, two, three and four fins, at three Reynolds numbers associated with turbulent flow, namely 8000, 10000 and 12000. The parameters which were chosen to be indicative of the thermal performance improvement in the internally finned absorber tubes are the Nusselt number, the friction factor, and the thermal performance factor. The modeling and simulation of the different scenarios were carried out on ANSYS Fluent software. The obtained results have demonstrated that the suggested geometric modifications at the level of the absorber tube successfully created turbulence in the flow and led to the improvement of the thermal performance factor by a maximum value of 1.134 and a minimum value of 1.045 as compared to the plain tube.

Keywords: PTR, heat transfer, thermal efficiency, finned absorber tube

Concentrating Solar Power Dish

This project is about designing a CSP Stirling dish capable of delivering power to a small-scale house or to cover a part of a house's energy needs, heating's electricity needs for instance; however, it will depend on the results we will obtain from our testing and simulation. The device will be designed by taking into consideration the solar irradiance (taken from weather data) over a period of time (daily, weekly, monthly). The study will analyze the energy output of the device if it is to be implemented in the Jabalpur region of M.P where solar radiation is significant, then we will compare it to the results obtained form the various material coating at the receiver. CSP dishes usually feature mirrors to reflect the sunlight but other alternatives are possible such as coating the collector with a reflecting material, for example stainless steel or polished aluminum. The coating material is critical in the design process as coating materials have different reflection coefficients, therefore, the operating temperature of the device will depend on it. The focal point of the parabolic dish is a cavity receiver containing a working gas that will be heated to start the Stirling engine. As its name indicates, the CSP Stirling dish uses an engine functioning with a Stirling thermodynamic cycle and operating at a temperature between 600 °C and 750 °C. The engine converts the thermal energy to a linear mechanical motion which will be turned to a rotary motion using a crank slider mechanism and then transferred to an electric generator converting the mechanical energy to electric power. The Stirling engine and the electric generator constitute one unit known as the Power Conversion Unit .

This work will tackle the issue by exploring all the parameters influencing the efficiency of the system and deeply analyzing the energy conversion process and the related equations. Indeed, we will analyze how the geometry affects the concentration ratio, then moving to the optical properties to finish with the functioning of our Stirling engine and the electricity generation.

Literature review

Comparative Study of Heat Transfer Enhancement in Parabolic Trough Collector Based on Modified Absorber Geometry Eric C. Okonkwo**;** Muhammad Abid**; and** Tahir A. H. Ratlamwala **2019**

The parabolic trough collector (PTC) is one of the most deployed and cost-effective solar concentrating systems available. The PTC under study is modeled after the LS-2 collector with different geometrically modified absorber tubes. The proposed model is validated using the Sandia national laboratory, AZTRAK, platform results. The absorber tube is modeled for five different geometry configurations: plain tube (smooth tube), longitudinal finned tube, a tube with a porous insert, a tube with a twisted tape insert, and a wavy (converging-diverging) tube. An analysis was conducted to observe the effects of these modifications on the thermal efficiency, Nusselt number, heat transfer coefficient, receiver temperature, and pressure losses. The converging-diverging absorber tube provides the maximum thermal enhancement of 1.16% whereas the absorber tube with porous insert yielded a mean enhancement of 0.89%. The results prove that modifying the inner geometry of the absorber tube leads to increased heat transfer coefficient and a reduction in the circumferential temperature of the receiver. The thermal and exergetic enhancement factors along with the exergetic efficiency are among other parameters investigated

Enhancing Thermal Performance of a Parabolic Trough Collector with Inserting Longitudinal Fins in the Down Half of the Receiver Tube 2020 Adel Laaraba & Ghazali Mebarki

Heat transfer in a finned absorber of a parabolic trough collector was studied numerically. The main aim of this work was to study the effect of attached fins on the enhancement of the thermal performance of a parabolic trough collector. The values of the fin's length varied from 0 to 20 mm; their thicknesses varied from 0 to 8 mm and their number was 5. The parameters used in the current study are: the thermal and dynamic field, friction coefficient, Nusselt number, the thermal efficiency and thermal enhancement index. Obtained results show that inclusion of fins to the lower half of the absorber tube can enhance the heat transfer between the absorber tube and working fluid. The increase of the fin's length increases the friction factor, Nusselt number and thermal efficiency, and the increase of fin's thickness also increases the previous parameters. Starting the value 6 mm of thickness, its effect remains the same, but thickness is less effective than length. The values 15 mm of length and 6 mm of thickness are selected as optimal values. Results show that the inclusion of the fins enhances the thermal performance of the parabolic collector by 8.45%.

Recent experimental enhancement techniques applied in the receiver part of the parabolic trough collector. O. AL-ORANp and F. LEZSOVITS 2020

Recently, the thermal performance of the parabolic trough collector (PTC), augmented to be more applicable and efficient, received intensive research. These studies aimed to improve heat transfer in the receiver part, in order to decrease the heat loss, and enhance the heat transfer to the thermal fluid. Many previous review papers focused on the numerical sides rather than the experimental side. Several research papers recommended doing more research in the experimental field; in order to decrease the gap between the numerical and experimental results, as well as increase the confidence level of what has been done in the theoretical field researches. Regarding the recommendations of the recent papers to decrease the gap between numerical and experimental aspects, this review paper focused on the recent experimental research related to thermal enhancement performance in the receiver part of the parabolic solar collector. In this research, different categories of the enhancement methods are discussed in detail through this review, namely nanofluids, surface modifications, and inserts models or the two categories combined together. We discussed these categories for different parabolic troughs considering only the recent experimental research between the period from 2014 up to 2019. Some parameters were discussed, such as the main dimensions of the examined receiver and parabolic collector. Moreover, types of nanoparticle specifications and preparation methods with different base fluids were highlighted. In addition, we discussed different aspects of using inserts models and inlet and outlet surface modification methods. Finally, the main thermal efficiency and thermal performance enhancement results for each work were presented.

METHODOLOGY OVERVIEW

The implementation of this Work consists of a series of methodic and well- structured steps. Figure 3.1.1 illustrates an overview of the main phases that this research work has gone through:

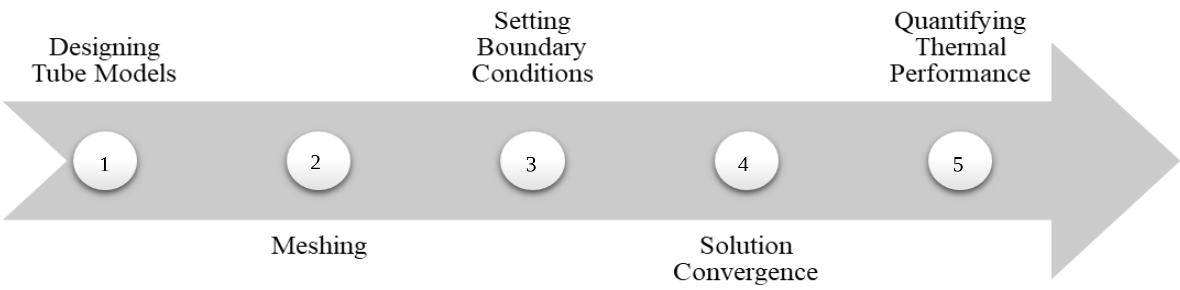


Figure 3.1.1Overview of the methodology adopted in this capstone Work

As shown in the figure above, the first phase is about designing the plain absorber tube and the finned tube models on ANSYS Fluent. The next step is devoted to meshing all the PTR models, i.e. dividing them into very finite elements that are suitable for the Finite element method (FEM) that the software uses to solve five differential equations. By solving those equations for every mesh element, a detailed description of the flow nature of the heat transfer fluid can be generated by means of several output parameters, including but not limited to average velocity of the HTF domain, pressure drop and outlet temperature. This is exactly the purpose of the fourth step, which is solution convergence: finding a sequence of solution values for every mesh element that is close to the exact solution while abiding by a pre- defined error tolerance or convergence criterion. Prior to solving and running the simulations on the numerical program, some boundary conditions shall be defined, such as the inlet temperature of the tube and the heat flux that this latter undergoes. At a final stage, the output data of the simulations is used to compute the three parameters (Nusselt number, friction factor and thermal performance factor) that will quantify the improvement in thermal performance efficiency of the PTR as a result of incorporating internal wall-attached fins within the absorber tube.

3.2 PHYSICAL MODEL

The model that was examined in this paper includes the receiver tube only, and doesn't take into consideration the characteristics of the reflective sheet or any other components of the parabolic trough collector.

Table 3.2.1 Specifications of the studied parabolic trough receiver

Quantity	Description	Unit	Value
LPTR	PTR length	m	2
D	Absorber tube diameter	m	0.064
TPTR	Absorber tube thickness	m	0.003

As shown in Table 3.2.1 and in Figure 3.2.1, the characteristics of the absorber tube chosen for this study comply with those of the commercially available PTRs. The tube is 2 m long, 3 mm thick and has an inner diameter of 64 mm. The PTR model is made of copper.

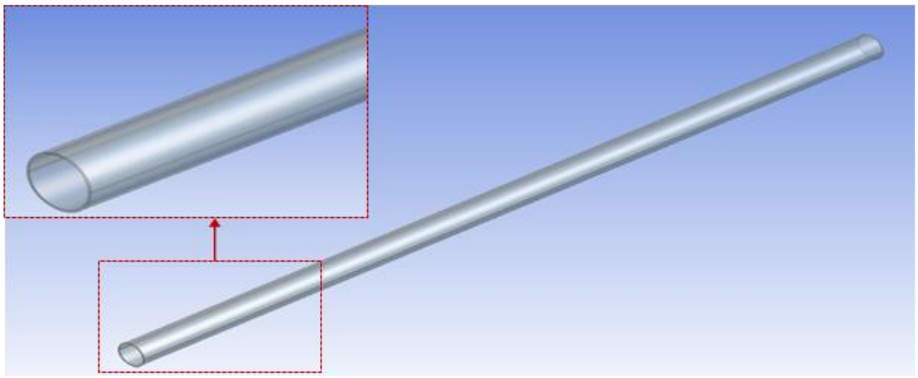


Figure 3.2.1 Geometrical model of the PTR under study

In order to assess the impact of internal fins on the heat transfer of the PTR, a total of 13 different models were designed (plain tube and twelve different finned tubes).

All fins have a triangular cross section and are extended along the whole tube. The length and width of the triangles is equal to 10 mm in all of the models. Three geometries were used for the fin that are right triangle finned tube (RTFT), isosceles triangle finned tube (ITFT) and obtuse triangle finned tube (OTFT) with an angle of 105°. In hindsight, the ITFT should have been called the acute triangle finned tube (ATFT), but for the rest of this report, we will stick with the ITFT designation.

At a first stage, the PTR models consisted of one fin for each triangle type. Then, two, three, and four evenly spaced fins were inserted into each one of the absorber models, to verify whether the number of internal fins affects the thermal performance of the parabolic trough receiver. Table 3.2.2 lists the twelve models which were designed on ANSYS Fluent.

Table 3.2.2Summary of the twelve finned tubes designed on ANSYS Fluent

Fin shape	One fin	Two fins	Three fins	Four fins
Right Triangle	RTFT	2RTFT	3RTFT	4RTFT
Isosceles Triangle	ITFT	2ITFT	3ITFT	4ITFT
Obtuse Triangle	OTFT	2OTFT	3OTFT	4OTFT

The twelve geometric models of the finned tubes designed on the CFD program are shown in Figure 3.2.2.

MESHING

The next step that comes after designing the models is meshing. This process is about discretizing the tube models into elements that are appropriate for the finite element method (FEM) that the CFD program uses to find an approximate solution to the differential equations governing the HTF dynamics. This phase of computational fluid dynamics analysis is of paramount importance because it directly affects the accuracy of the generated simulation results.

Generally, the mesh element size was chosen to be 5 mm. Yet, for some critical regions of the fluid domain and absorber tube, which experience more complex flow conditions and hence require additional accuracy, two sophisticated methods were employed, namely inflation and edge sizing.

The first tool, also called boundary layer refinement, allows for the proper discretization of the viscous sublayer of the fluid that is immediately adjacent to the inner wall of the absorber tube, as shown in Figure 3.3.1. Therefore, ten inflation layers were added to the tube models with a first layer thickness of 0.08 mm and a growth rate of 1.4.

As for edge sizing, it makes it possible to specify a local growth rate for the cells that spread away from the edges of the metallic absorber tube. This local rate is different from the global growth rate of the tube model and usually exceeds it mainly because mesh elements near the edges require a higher precision, and need a smaller mesh size accordingly. Different growth rates were used for the various edges of the tube models, especially the finned ones.

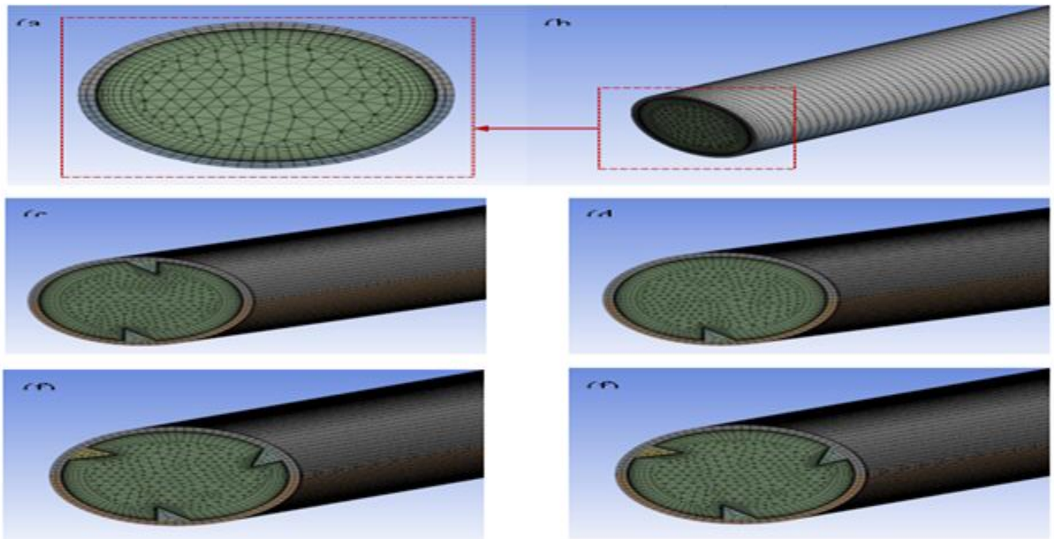


Figure 3.4.1 represents a sample of meshes that were generated for the plain tube (PT) and the tubes equipped with one, two, three and four right-angle triangular fins

BOUNDARY CONDITIONS

Quantity	Boundary conditions	Position	Value
Tin	Inlet temperature	Tube inlet	600 K
ṁ	Inlet mass flow rate	Tube inlet	0.145, 0.181, 0.217 Kg/s
Pout	Outlet pressure	Tube outlet	5 Pa
QTop	Constant heat flux	Top tube section	750 W/m^2
QBottom	Constant heat flux	Bottom tube section	19 500 W/m^2

RESULTS AND DISCUSSION

The number of simulations performed on ANSYS Fluent in the context of this study amounts to 39 simulations. For every one of the 13 tube models, simulations were run for three Reynolds numbers that are 8000, 10000 and 12000 respectively.

For each simulation, four output parameters were retrieved from the CFD program and later used in the calculation of the three indicators of heat transfer enhancement, that are the Nusselt number (Nu), the friction factor (f), and the thermal performance factor (η). The four output quantities which were obtained from ANSYS Fluent simulations are fluid outlet temperature (Tout), average temperature of the heat transfer fluid domain within the absorber tube (Tm), average temperature of the receiver (Tw) and the pressure drop along the tube (ΔP).

DATA VALIDATION

This procedure, consisting of data validation, is key to having a high degree of confidence about the obtained results. Therefore, the values of the Nusselt number and friction factor for the plain tube that are obtained by employing equations (7) and (8) and using the CFD outputs are to be checked for accuracy. This check is done by re-calculating the two quantities theoretically by means of Dittus-Boelter and Blasius correlations, referred to by equations (10) and (11) respectively.

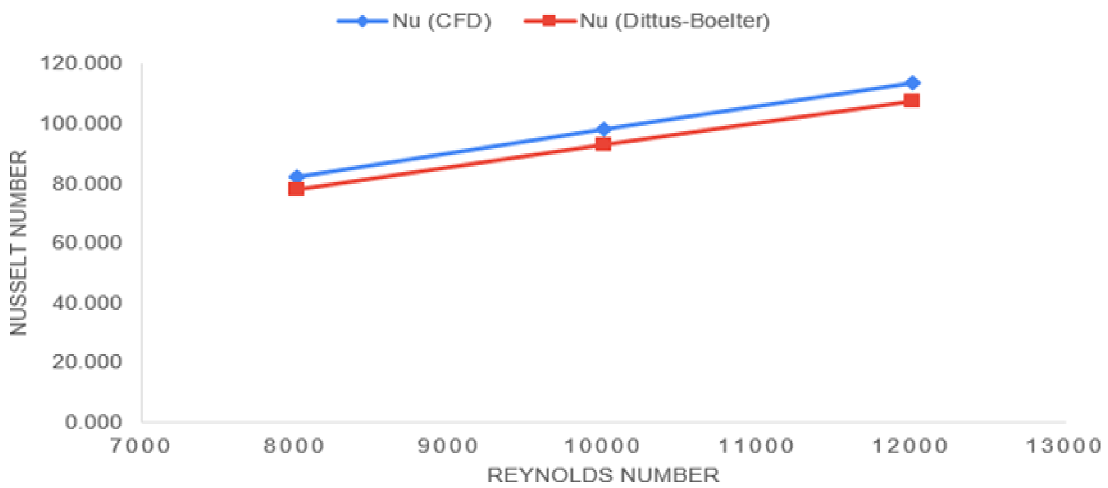


Figure 4.2.1 Nu calculated with CFD vs Nu calculated with Dittus-Boelter equation

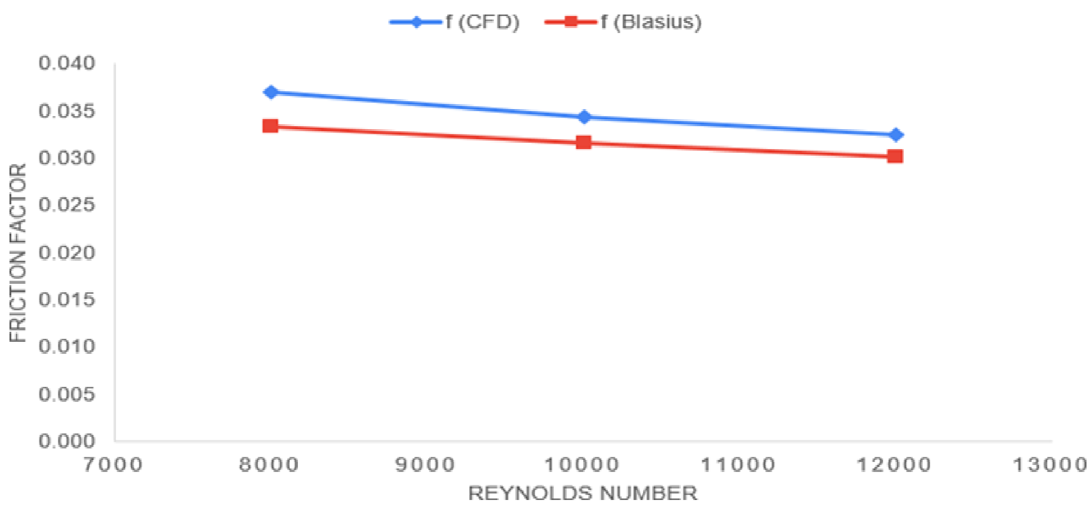


Figure 4.2.2 f calculated with CFD vs f calculated with Blasius equation

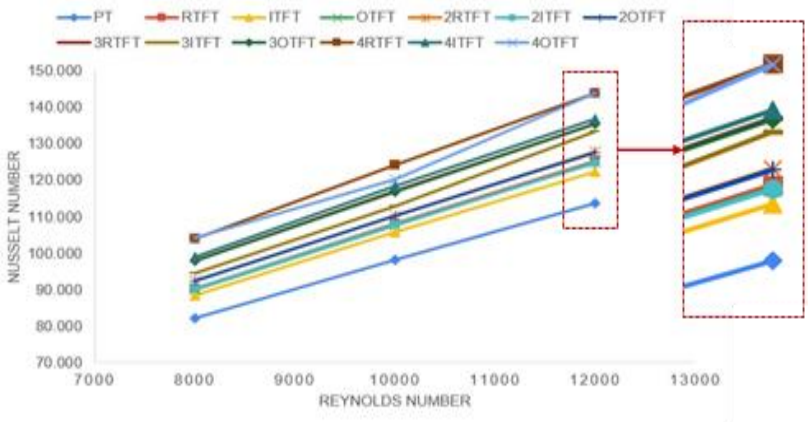
As clearly shown in the two graphs, the CFD and empirical calculations for both Nu and f do agree with each other. The average standard deviation values turned out to be 5.59% and 8.68% for Nusselt number and friction factor respectively. This being said, it can be safely concluded that the accuracy of the numerical model at hand falls within the acceptable range.

THERMAL PERFORMANCE ANALYSIS

Nusselt number analysis

The Nusselt number is defined as the ratio of convective to conductive heat transfer at a boundary in a fluid under the same conditions, as illustrated in equation (7). In simple terms, a high Nusselt number would indicate in our case that more heat was transmitted from the absorber tube to the heat transfer fluid. And this is exactly why this parameter was chosen to prove whether the introduction of fins into the inner wall of the parabolic trough receiver would enhance the heat transfer efficiency of the system under study or not.

Figure 4.3.1 is a graph that illustrates the Nusselt number values obtained for the plain tube and the twelve finned tubes for 8000, 10000 and 12000 Reynolds numbers.



There are four main observations that can be drawn from the above graph.

The first one is that as Reynolds number increases, the Nusselt number get higher too for all cases. This implies that the more turbulent the fluid flow is, the better it is for the heat transfer between the absorber tube and the HTF.

The second remark is that the Nusselt number values of internally finned tubes are all higher than that of the plain tube. This naturally leads to the conclusion that the insertion of fins into the PTR does indeed increase the efficiency of the heat transfer of the system.

The third observation consists of the fact that the more fins that are introduced into the absorber tube, the higher the Nusselt number gets. For instance, the Nusselt numbers associated with tubes containing three fins are higher than those related to two-finned tubes for all triangle shapes. In the same way, two-finned tubes have yielded bigger Nusselt numbers than one-finned absorbers. It is worth mentioning that among the twelve finned tubes and at a Reynolds number of 12000, the tube containing four right triangle fins (4RIFT) has recorded the highest Nusselt number that amounts to 143.873, followed by the 4OTFT with a value of 143.822. Whereas the lowest Nusselt number value is equal to 122.345 and occurs at Re = 8000 for the tube equipped with one isosceles triangle fin ITFT.

The final deduction is that the Nusselt number values that are associated with obtuse and right-angle triangular fins are pretty close to each other and they significantly exceed those linked to isosceles triangular fins.

Friction factor analysis

The friction factor indicates pressure drop of the HTF in the tube as a result of the interactions between the fluid and the absorber, as demonstrated by equation (8). In other words, by increasing the number of collisions between the fluid particles and the solid particles of the pipe, more heat will be transferred from the PTR to the working fluid. This shall explain the rationale behind this study: introducing fins to the inner wall of the tube will increase the contact surface area between the HTF and the PTR and improve the heat transfer efficiency as

such. This means that the higher the friction factor, the better the heat transfer is expected to take place.

Yet, the downside of an increasing friction factor is the loss of pressure at the level of the heat transfer fluid, which implies that a bigger pumping work will be required to drive the system.

Figure 4.3.2 is a graph that illustrates the friction factor values obtained for the plain tube and the twelve finned tubes for 8000, 10000 and 12000 Reynolds numbers.

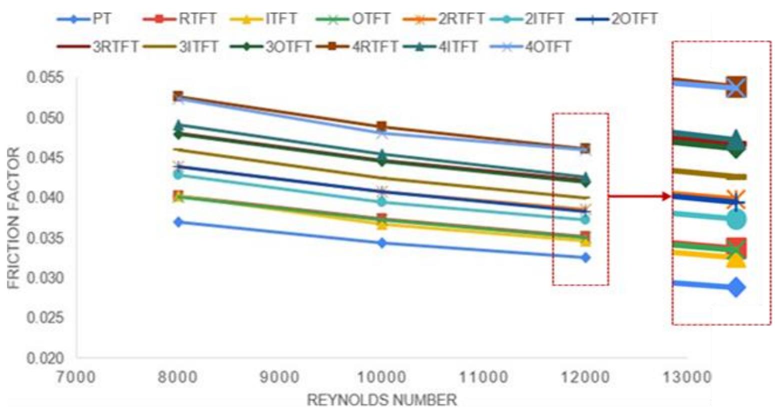


Figure 4.3.2 f vs Re for plain tube and finned tubes

Similar to the Nusselt number analysis, there are four major conclusions that can be deduced from Figure 4.3.2.

From the very first glance, it is clear that the friction factor decreases with increasing Reynolds numbers. This is exactly the type of correlation that exists between Reynolds number and the friction factor for turbulent flow.

Besides, the graph obviously demonstrates that the friction factor values for the finned absorbers all exceed the f value of the plain tube. This confirms one more time that the geometric modifications adopted in this research cause the friction factor to increase and have the potential to bring about an improvement in the thermal performance of the PTR.

The third remark is that the higher the number of fins within the tube, the bigger the friction factor value gets, and the better it affects the heat transfer efficiency of the parabolic trough receiver. At Re =8000, the 4RTFT has generated the highest friction factor value that equals 0.053, followed by the 4OTFT with a value of 0.052, and the 4ITFT ranked third with a friction factor of 0.049. The smallest friction factor value among the finned tubes amounts to 0.035 and is associated with RTFT, OTFT and ITFT at Re = 12000.

Fourth, it is noticed from the graph that the highest friction factor values are related to right- angle and obtuse triangular fins, whereas isosceles triangular fins have scored the lowest friction factor values.

Thermal performance factor analysis

The thermal performance factor (η) is the ultimate indicator of the heat transfer enhancement of the PTR in this study and also in all of the research works covering similar topics. This is because it captures both the enhancement in the Nusselt number and in the friction factor of the internally finned tubes as compared to the plain tube, as illustrated by equation (9). It reflects how well the parabolic trough receiver does in terms of transmitting the heat received from the sun to the working fluid and keeping thermal losses to a minimum. It goes without saying that the increase in the thermal performance factor necessarily means an improvement in the heat transfer efficiency of the finned tube.

Figure 4.3.3 displays the thermal performance factor values generated for the twelve finned tubes for 8000, 10000 and 12000 Reynolds numbers.

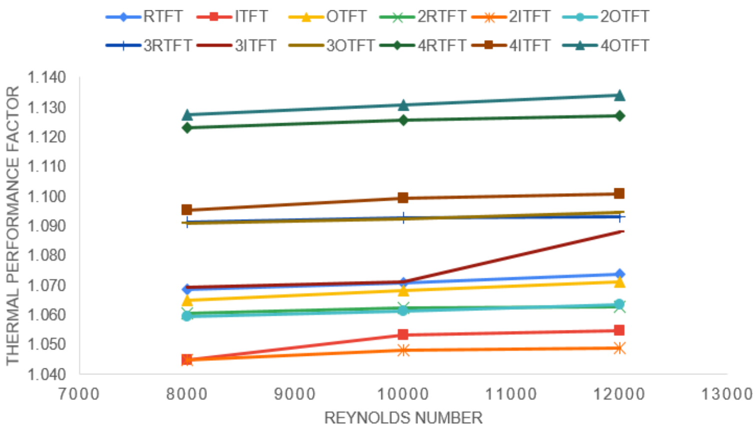


Figure 4.3.3 Thermal performance factor (η) vs Re for the finned tubes

According to the acquired results, the values of thermal performance factor for all twelve scenarios exceed one. Therefore, the measure which is examined in this study and consisting of modifying the internal geometry of the tube impacts the heat transfer efficiency positively, regardless of the number of fins inserted into the tube.

It is also evident from the above graph that the use of four fins in all cases yields the highest increase in the thermal performance factor, followed by three fins. Interestingly, tubes containing one fin outperform those equipped with two fins in terms of heat transfer efficiency for every triangular fin shape.

The highest thermal performance was achieved by the 4OTFT at Re = 12000 with a value of

1.134. For the same Reynolds number, the 4RTFT ranked second and the 4ITFT came third with η values of 1.127 and 1.101, respectively. As for the lowest value of thermal performance, it was recorded by the ITFT at Re = 8000 with a value of 1.045. So generally speaking, finned tubes that are equipped with obtuse and right-angle triangular fin shapes engender a better improvement in the heat transfer efficiency than tubes having isosceles triangular fins. Nonetheless, the increase of the Reynolds number doesn't seem to have a significant effect on the thermal performance factor. As portrayed in the graph, the curves look almost horizontal with very few exceptions. This suggests that the impact of the fin shape and the number of fins on the thermal performance of the PTR is much stronger than the influence of the Reynolds number.

TEMPERATURE GRADIENT ALONG THE PTR

As mentioned previously, the parabolic trough receiver is subject to a non-uniform heat flux. This causes the bottom part of the receiver to be hotter than the top part. Yet, the insertion of internal fins into the tube will solve this issue because this measure enables the fluid flow turbulence to increase and hence allows for a more homogeneous temperature distribution along the absorber tube, as illustrated by Figure 4.4.1. A lower temperature gradient leaves no room for the metallic tube to bend or the glass envelope surrounding it to break [9]. This also decreases the chances of the system failure as a whole.

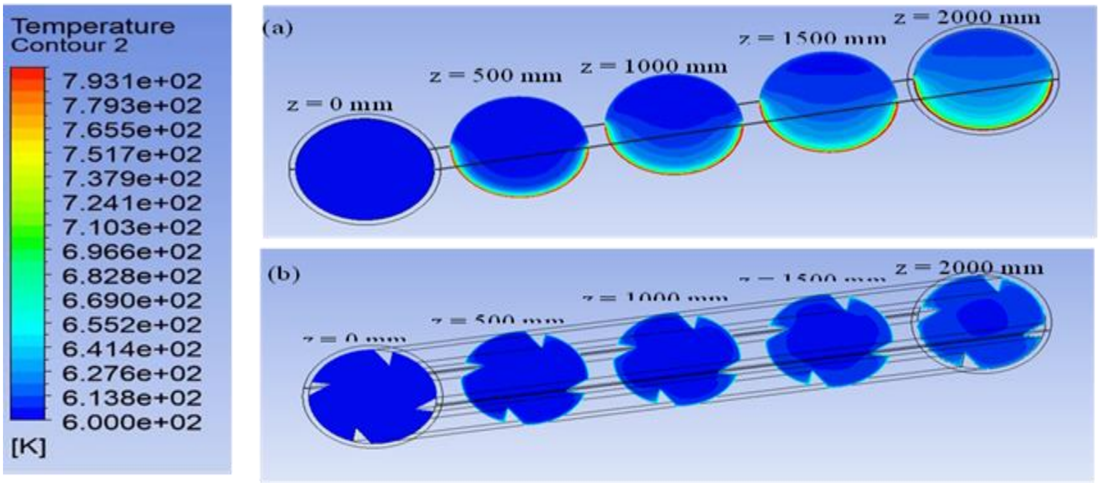


Figure 4.4.1 Temperature contour at Re = 12000 for: (a) PT (b) 4RTFT

The above Figure represents a temperature contour for the plain tube and the tube containing four right-angle triangular fins at Re = 12000. The contour planes are located at z = 0, 500, 1000, 1500 and 2000 mm along the PTR. Only one finned tube model was chosen for the comparison with the plain tube mainly because all the finned PTRs have generated almost the same results when it comes to temperature distribution along the tube.

DISCUSSION OF THE RESULTS

The results of the simulations carried out on ANSYS Fluent for the plain tube and the twelve finned tube models and the subsequent calculations of Nu, f, and η reveal with high confidence that placing triangular fins within the parabolic trough receiver does improve its thermal performance.

Some of the main observations to be made are that obtuse and right-angle triangular fins have outperformed the isosceles triangular fin in terms of the overall thermal performance of the absorbers; and that, the more fins are placed within the tube, the better the heat transfer efficiency becomes. This doesn't necessarily apply to the case where the number of fins is below two, because the η values of one-finned tubes slightly exceeded those associated with two-finned tubes.

The geometric modifications investigated in this study increase the contact surface area between the fluid domain and the inner wall of the tube, result in a more turbulent HTF flow and permit the transmission of more solar heat from the PTR to the working fluid. Such a significant outcome was attained thanks to a simultaneous increase in the Nusselt number and the friction factor of the tubes, and a rise in the thermal performance factor as a result of that.

However, the increase in the fiction factor is accompanied with a disadvantage related to the pressure drop within the PTR. The issue is that the loss of pressure means that a bigger pumping power will be required, which is eventually translated into a higher electricity consumption during the system operation.

In order to decide whether the insertion of fins into the tube is worth it or not, a more thorough study shall be conducted to check if the benefit of the geometric alteration of the PTR and the corresponding thermal performance enhancement compensate for the rise in the electricity usage. The report at hand cannot answer such a question because it is outside the scope of this research. Besides, it was also noticed that the increase in the Reynolds number didn't have much of a positive effect on the heat transfer enhancement of the system. In practical terms, the increase in the Reynolds number is expressed as a higher mass flow rate at the inlet of the tube, which means again more pumping work. Thus, it is safe to conclude that raising the pumping power is unnecessary in this case, given its little impact on the thermal performance of the heat transfer fluid.

Furthermore, it is important to highlight the fact that introducing wall-attached internal fins to the absorber tube is a very economically viable measure, as compared to the use of nanofluids as a HTF for instance. That is because the dimensions of the fins are negligible as compared to the whole PTC system, and as a consequence, the increase in the manufacturing cost due to the incorporation of fins is not expected to be that significant. This further encourages the implementation of this measure in order to improve the efficiency of parabolic trough collector plants. However, despite the obvious increase in the heat transfer efficiency of the PTR as a result of introducing fins, a more elaborate investigation shall be held so as to find out whether the increase in the system efficiency and the additional energy outcome of the system resulting from that, surpass the additional manufacturing costs associated with the insertion of fins into the parabolic trough receiver.

On a final note, the measure examined in the context of this research work could be regarded as a constructive suggestion to improve the quality of PTC systems. The geometric modification proposed in this study can be applied to already existing parabolic trough receivers, and this way, there wouldn't necessarily be a need to give up on the PTRs existing in the market, in case this measure were to be embraced and executed. Those PTRs will be just upgraded by introducing internal fins into them, rather than destroyed or abandoned.

CONCLUSION

In this Work a numerical study is conducted to examine the impact of inserting wall- attached internal triangular fins into a parabolic trough receiver.

Three types of triangular profiles were selected for the fins that are:

1. Right-angle triangle,
2. Obtuse triangle
3. Isosceles triangle with an angle of 105°.

Also, three Reynolds numbers were used for a turbulent flow, that are 8000, 10000 and 12000. Besides, simulations were conducted on the CFD program, ANSYS Fluent, for tubes with 1, 2, 3 and 4 fins, and the results were compared with those of the plain tube model. The chosen parameters to indicate an improvement in the heat transfer efficiency of the finned tubes are the Nusselt number (Nu), the friction factor (f) and the thermal performance factor (η).

The main conclusions can be epitomized as follows:

1. The insertion of internal fins into the PTR does improve the heat transfer efficiency by increasing the flow turbulence.
2. The highest Nu value was recorded by the 4RTFT at Re = 12000.
3. The highest f value was achieved by the 4RTFT at Re = 8000.
4. The highest η value was obtained for the 4OTFT at Re = 12000.
5. Obtuse and right-angle triangular shapes of the fin have demonstrated the best results for all three parameters whereas the isosceles triangular fin has recorded the lowest thermal performance overall.
6. Nu and f increase with the Reynolds number, when this latter does not affect efficiency that much.
7. Generally speaking, placing more fins within the absorber tube leads to a better thermal performance of the system.
8. The growth in the friction factor comes with the disadvantage of pressure drop which implies the need for a superior pumping power for the PTC operation.

FUTURE WORK

This work probably will be further polished and accompanied by carrying out more accuracy investigation techniques, such as grid independence test. Also, more simulations with more Re numbers and a greater number of fins can be conducted to confirm the gained outcomes & also different profile of fins and have a more impression about the impact of different parameters on the thermal performance of parabolic trough collectors.

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